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Research Article

Utilization of high volume of cockle shell as sand replacement in bricks: Effects on density, compressive strength, water absorption and initial rate absorption

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Abstract

The construction industry's dependence on natural sand has raised environmental concerns, leading to research on alternative sand replacement. This study investigates the incorporation of high-volume replacement of cockle shells (ranging between 30% - 100% replacement by volume) as a partial fine aggregate replacement in cement-sand brick production. Brick testing conducted includes brick density, compressive strength, water absorption and initial rate absorption. The constituent material testing revealed that cockle shells have a higher density (1687.27 kg/m^3) than sand (1642.67 kg/m^3) and a specific gravity of 2.73, contributing to improved compactness in the brick matrix. The results indicated that the compressive strength increased from 7.93 to 13.83 MPa at 28 days for 60% cockle shell replacement, while water absorption and IRA were reduced by about 50% (from 14 to 7%) and 50% (from 10.55 to 5.09 kg/m^2/min), respectively. However, beyond a 60% replacement, strength declined due to increased porosity, with 100% recording a strength of 7.17 MPa at 28 days. The results suggest enhanced compactness and reduced water uptake at 60% CS replacement. All brick specimens exceeded the JKR minimum compressive strength requirement of 5.2 MPa, with the optimum mechanical and durability performance found at 60% CS replacement. Including these performance metrics provides practical clarity for material selection and highlights the engineering viability of cockle shells in sustainable construction. This study confirms the potential of cockle shell waste as an eco-friendly, high-volume sand replacement, supporting both environmental preservation and circular economy practices.

1. Introduction

The construction industry plays an important role in economic development, yet it is one of the largest contributors to environmental degradation due to excessive resource consumption and waste generation. Therefore, there has been a growing interest among researchers in exploring sustainable and eco-friendly materials to reduce environmental impact and dependence on natural resources. In Malaysia, sustainability has become a national priority, and the government actively

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promotes green initiatives. The Twelfth Malaysia Plan (RMK-12) sets a clear pathway for Malaysia to achieve a zero-carbon by 2050, emphasizing the integration of green technology, eco-friendly products and improving waste management to establish a sustainable circular economy. Thus, to support the agenda, the 2024 National Budget allocated RM2 billion to accelerate the transition toward zero-carbon and sustainable development [1].

Brick remains one of the most extensively used construction materials worldwide due to its availability, cost-effectiveness, and suitability for both structural and non-structural purposes [2,3]. The global demand for bricks continues to rise, particularly in developing countries experiencing rapid urbanization, such as Bangladesh [4]. According to [5,6], global brick production reaches approximately 1,391 billion units annually, with demand expected to continue rising. Similarly, [7] reported that brick production accounts for around 1.3 trillion units worldwide, with Asia being the largest producer, supplying over 75% of the global demand. In Malaysia, clay bricks and sand bricks are widely used in the construction industry due to their availability, cost-effectiveness, and suitability for various structural applications [8]. However, cement-sand bricks are more commonly used, especially in the construction sector, as they are easier to produce and more economical compared to clay bricks [9]. However, conventional brick production is resource-intensive, with significant environmental drawbacks.

The material used for cement sand brick is sand, cement and water, where sand is the most essential component. According to [10], the standard mix ratio for cement-sand bricks consists of six (6) parts sand to one (1) part cement by volume. The manufacturing process depends largely on river sand. Unfortunately, excessive dependence on natural sand has led to several environmental and economic concerns. A study by [11] showed that sand mining has caused the destruction of riverbeds, significantly impacting local ecosystems and water quality. In addition, [12] also found that continuous mining without proper management has resulted in unsustainable resource depletion, causing long-term environmental damage. [13] reported that several countries are already experiencing severe sand shortages due to excessive extraction.

In response to these challenges, recent research has explored the incorporation of industrial and agricultural waste material into brick production as a strategy to reduce dependence on natural resources. One promising approach involves utilizing cockle shell, an abundant by-product of the seafood industry, as a sand replacement in cement-sand brick. According to [14], production of cockles had increased from 9596.76 tonnes in 2016 to 18,674.39 tonnes in 2020. The processing of cockles, whether for canned products or fresh market distribution, generates a large amount of discarded shells, which are typically treated as waste [15]. According to [16], the cockle shell has very low commercial value, so it is often disposed of in the landfill area, creating environmental challenges, such as unsanitary conditions, which may promote the spread of diseases. On top of that, utilizing the by-product as a raw material in construction products would reduce the amount of waste ending up in landfill and contribute towards a cleaner environment.

Cockle shells have been shown to positively influence the mechanical properties of concrete and mortar mixes. [17] reported that replacing up to 30% of fine aggregate with cockle shells significantly enhanced compressive strength and overall durability in mortar applications. Similarly, [18] observed that incorporating 10% to 40% cockle shells as a sand replacement in mortar led to an increment in compressive strength. Those studies have demonstrated the potential of cockle shells as a partial sand replacement, however, they are limited to replacement levels below 30-40%, leaving a significant research gap in understanding the effect on the incorporation of high-volume cockle shells as sand replacement in the cementitious product. Exploring high-volume replacement is essential for maximizing waste utilization, reducing reliance on natural sand, and mitigating environmental concerns associated with sand mining and shell waste disposal. In addition to cockle shells, various studies have examined high-volume sand replacements using different materials. For instance, [19] investigated the incorporation of high-volume palm oil clinker as a sand replacement and found that up to 50% replacement improved both compressive and flexural strength in bricks. Furthermore, [20] demonstrated that recycled concrete aggregate can serve as an effective high-volume sand replacement. Their results indicated that replacing natural sand with 55% recycled concrete aggregate provided the highest compressive and flexural strength compared to other replacement levels and the control specimen.

According to [21,22], cockle shell is suitable to be the material replacement in the concrete mixture because of the high calcium carbonate ($CaCO_3$) content, which is more than 90%. The calcium carbonate gives the shell structure a high strength, low mass and low coefficient of thermal conductivity [23]. [24] emphasized that utilizing cockle shells as a partial fine aggregate or cement replacement not only mitigates waste accumulation but also enhances the mechanical properties of concrete, reinforcing its potential as an eco-friendly alternative in brick production. Therefore, this study aims to investigate the incorporation of high-volume cockle shells as sand replacement, with the goal of identifying the optimum replacement level that satisfies the standard while promoting a sustainable approach.

2. Experimental Works

This section describes the experimental work investigating the effectiveness of utilizing a high volume of cockle shells as fine aggregate replacement in cement-sand brick production.

2.1. Testing Series Investigated

Each testing series was prepared with three testing specimens using mould size of 215mm in length, 103 mm in width and 65 mm in height. Cement-sand brick with the composition ratio of six (6) parts sand to one (1) part cement by volume was prepared with the fine aggregate partially replaced with cockle shell, whereas the water-cement ratio used was 0.5. The replacement of CS as fine aggregate replacement was 0%, 30%, 40%, 50%, 60%, 70%, 80%, 90% and 100%. Testing series invested were listed in Table 1.

Table 1. Testing series investigated in the present study

CS Replacement (%)	Testing designations
0	CS0%
30	CS30%
40	CS40%
50	CS50%
60	CS60%
70	CS70%
80	CS80%
90	CS90%
100	CS100%

2.2. Preparation of Cockle Shell (CS) as Fine Aggregate Replacement

The disposed CS was collected from the dump area in Sungai Rengit, Batu Pahat, Johor. Efforts were taken to minimize material variability and ensure consistency of the cockle shell (CS) used. All CS were collected from the same local source and batch to maintain uniformity in origin. Prior to processing, the shells were thoroughly washed to remove impurities and organic matter, then dried under controlled conditions to reduce moisture-related inconsistencies. Fig. 1 shows the preparation of CS as a fine aggregate replacement in the cement-sand brick production. The collected shell has been cleared from leftover flesh, washed and dried for 24 hours. After that, the cockle shell was crushed using a milling crusher machine before sieving to pass 5 mm.

2.3. Testing of Constituent Material

In this experiment, the testing material properties refer to the sieve analysis, specific gravity test and density test for sand and CS as fine aggregate replacement in the cement-sand brick production. The passing sample of 5 mm sieves was used as fine aggregate replacement in cement-sand brick. The size distribution of sand and CS as fine aggregate replacement were sieved and underwent the sieve analysis based on the [25] to determine whether it is compatible to be used as fine aggregate replacement in the cement-sand brick production.

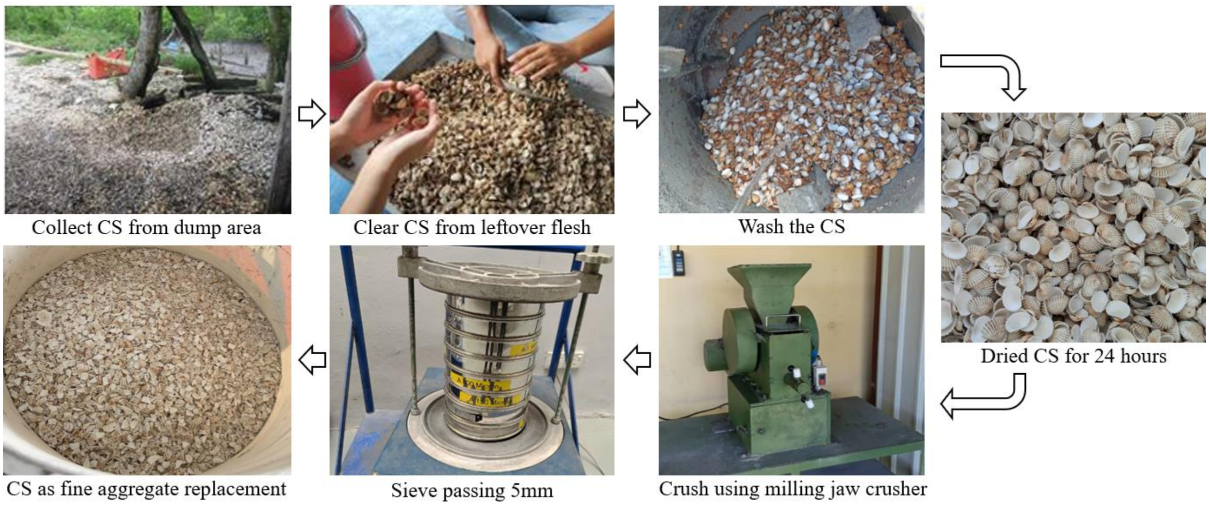


Fig. 1. Preparation of CS as fine aggregate replacement

Fig. 2 indicates the specific gravity and density tests for the materials used in these experiments, conducted according to ASTM C128. The specific gravity test determines how dense a material is compared to water. Materials with lower specific gravity tend to have higher porosity and water absorption, which can affect their overall strength and durability. The density of the material plays a crucial role in determining its mass per unit volume, influencing the overall weight and structural performance of the final product.

(a) (b)

Fig. 2. (a) Specific gravity test (b) density test

2.4. Testing for Brick

Testing for bricks was divided into four parts: density testing, compression testing, water absorption testing, and initial rate absorption (IRA) testing. Fig. 3 illustrates the testing conducted for the brick. The density testing determines the mass per unit volume of brick, which influences the strength and load-bearing capacity. Compression testing measures the maximum load that can be sustained by the brick before failure, ensuring that the brick meets the standard requirements. The compression test, conducted according to [26], measures the maximum load a brick can withstand before failure, ensuring it meets standard requirements. This test was performed after 7 days and 28 days of curing. Since Malaysia follows the standard specifications set by JKR, the compression strength of the brick must be greater than 5.2 MPa.

The water absorption test was conducted according to [26] after 28 days of curing, to evaluate the brick's porosity and ability to retain moisture, directly affecting its durability and resistance to weathering. The voids between the constituent materials influence water absorption. According to [27], the water absorption of a brick must not exceed 18%.

The initial rate of absorption (IRA) test was conducted after 28 days of curing, following [28]. This test assesses how quickly a dry brick absorbs water, which is crucial for proper bonding with mortar in masonry applications. The test was performed on day 28 of curing. The brick specimens were oven-dried at 110°C to 115°C for at least 24 hours, then cooled and weighed. The base of each brick was levelled and placed flatwise on two noncorrodible metal rods in a tray. Clean water was added to a level of 3 mm above the rods, and the brick was brought into contact with the water. After 1 minute ± 1 second, the brick was removed, surface moisture was wiped using a damp cloth, and the brick was immediately reweighed.

(a) (b) (c)

Fig. 3. (a) Compression test, (b) Water absorption test, (c) Initial rate absorption (IRA) test

2.5 Scanning Electron Microscopy (SEM)

Scanning electron microscopy was carried out to examine the shape of sand and cockle shell particles, and also the morphologies of failed brick specimens at various cockle shell contents. The SEM was conducted using a ZEISS GeminiSEM 460 at an operating voltage of 11.5 kV as in Fig. 4. Before scanning, the specimens' surfaces were thin-coated with gold to increase the electrical conductivity.

Fig. 4. SEM Machine (ZEISS GeminiSEM 460)

3. Results and Discussion

This section presents experimental observations and discusses the results obtained from testing of the constituent materials and all tested series investigated.

3.1. Mechanical Properties of Sand and Cockle Shell (CS) AS Fine Aggregate Replacement

This sub-section details the constituent material tests for sand and cockle shells, specifically focusing on sieve analysis, density, and specific gravity testing.

3.1.1 Sieve Analysis for Sand and Cockle Shell (CS)

Fig. 5 presents the particle size distribution of sand and cockle shell (CS), highlighting a notable difference in gradation between the two materials. The sand exhibits a well-graded profile, with its curve positioned between the upper and lower limit boundaries, indicating a balanced distribution of fine and coarse particles essential for optimal packing density, minimal void content, and enhanced interlocking, which collectively contribute to mechanical strength and durability. The smooth gradation of sand confirms its compliance with standard specifications for fine aggregate in construction. In contrast, the CS curve reflects a coarser material with a lower passing percentage in the finer sieve ranges, indicating a deficiency of fine particles. Despite this, the overall particle size distribution of the cockle shell (CS) remained within acceptable limits, indicating its compatibility as a sand replacement. In this study, the CS was thoroughly cleaned, oven-dried, and mechanically crushed using a jaw crusher, followed by sieving through a 5.00 mm sieve to control the maximum particle size. To maximize consistency, all CS samples were ground using the same grinding machine, and only material passing the 5.00 mm sieve was used in the mix. The retained particles generally ranged from 2.0 mm to 4.75 mm, closely resembling the size range of natural sand. Although this gradation was applied consistently across all mix designs, some variation in particle shape and texture occurred due to the nature of the crushing process, which produced irregular and angular particles. As a result, slight inconsistencies in packing density and pore structure among different mixes may have occurred, however, the overall gradation remained within a typical fine aggregate range and was considered acceptable for comparative analysis across the replacement levels.

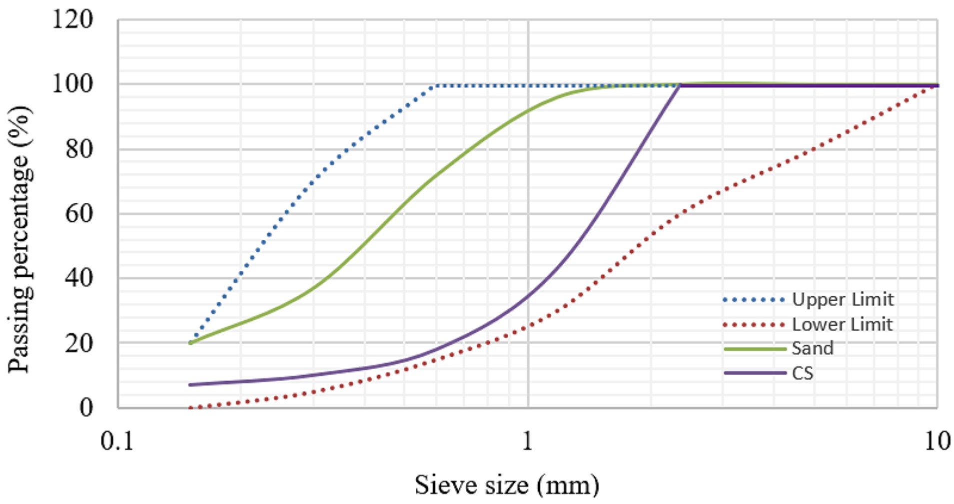


Fig. 5. Particle size distribution of sand and CS (mm)

3.1.2 Density of Constituent Materials

Table 2 indicates that cockle shells (1687.27 kg/m^3) have a slightly higher density than sand (1642.67 kg/m^3), while cement (1478.8 kg/m^3) exhibits the lowest density among the three. This suggests that replacing sand with cockle shells in brick production may result in denser and potentially heavier brick. However, the impact of cockle shell replacement extends beyond density, as its particle shape and packing efficiency may affect overall porosity and water absorption. While a reduction in density can be beneficial for lightweight construction, it must be carefully managed to maintain mechanical properties, such as compressive strength. Previous studies emphasize that optimizing the combination of high- and low-density materials is crucial for balancing mechanical strength and water absorption.

Table 2. Measured density of the materials used in the present study

Material	Density (kg/m^3)
Cement	1478.8
Cockle shell	1687.27
Sand	1642.67

3.1.2 Specific Gravity of Constituent Materials

Table 3 presents the specific gravity of the materials used in this experiment. The results indicate that cement has the highest specific gravity (3.32), followed by cockle shell (2.73) and sand (2.66). The higher specific gravity of cockle shell compared to sand may contribute to improved compactness in the mix, particularly at moderate replacement levels.

Table 3. Specific gravity of the materials used in the present study

Material	Specific Gravity
Cement	3.32
Cockle shell	2.73
Sand	2.66

3.1.3 Water Absorption of Sand and Cockle Shell as Sand Replacement

Table 4 represents the water absorption of the sand and cockle shell as sand replacement in this experiment. The result shows the cockle shell has higher water absorption compared to the sand. This is because of the porous structure and irregular surface texture of the cockle shell which allows more water to be absorbed and retained.

Table 4. Water absorption of the materials used in the present study

Material	Water Absorption (%)
Cockle shell	3.12
Sand	1.33

3.2. Brick Testing

This sub-section details the brick testing conducted, which includes density, compressive, water absorption and initial rate absorption (IRA).

3.2.1 Density of Bricks

Table 5 presents the density results of cement-sand brick incorporating different percentages of CS as sand replacement. The density was measured at 7 days and 28 days, with percentage differences compared to the control mix (CS0%). The results indicate a distinct trend in density variation with increasing CS content.

Table 5. Measured density of all testing series investigated

Design Mix (%)	Density for 7 days	Density change* (%)	Density for 28 days	Density change* (%)
CS0	1928	-	1932	-
CS30	1954	1.35	1970	1.97
CS40	1994	3.42	2011	4.09
CS50	2010	4.25	2020	4.55
CS60	2014	4.46	2047	5.95
CS70	1991	3.27	1994	3.21
CS80	1967	2.02	1863	-3.57
CS90	1813	-5.96	1855	-3.99
CS100	1811	-6.07	1823	-5.64

* as compared to the control mixture, CS0%

Fig. 6 shows a trend of density where the density increases as the cockle shell content increases for both 7 days and 28 days, curing from CS0% to CS60% and then decreases in the mixes containing more than 70% sand replacement, i.e., CS70% until CS100%. The density of the brick increases upon increasing the amount of cockle shell up to 60%, which was due to the higher specific gravity of the CS compared to the natural sand. Aligned with the study of [29,30], which stated that the use of the material with lower density is prone to lowering the density value. However, the density starts to decrease from 70% to 100% of the replacement because it is likely attributed to the higher porosity and lighter nature of cockle shells, which increases the void content within the mix. As the CS content increases, these voids become more pronounced, resulting in a decrease in the overall density of the mix. This trend is particularly noticeable at CS90% and CS100%, where the absence of sand and the increased proportion of cockle shell led to a marked reduction in density. A similar trend is observed in the study by [31], where density initially increases with the inclusion of cockle shell (CSP) but declines at higher replacement levels (CSP10CB and CSP15CB) for a 1:3 brick. The density reduction is attributed to the increased porosity CSP consists mainly of calcium carbonate ($CaCO_3$), which does not actively contribute to calcium silicate hydrate (C-S-H) formation, the key binding phase in cement hydration. Consequently, excessive CSP disrupts the matrix's packing efficiency, leading to a less dense microstructure with increased voids and weaker inter-particle bonding.

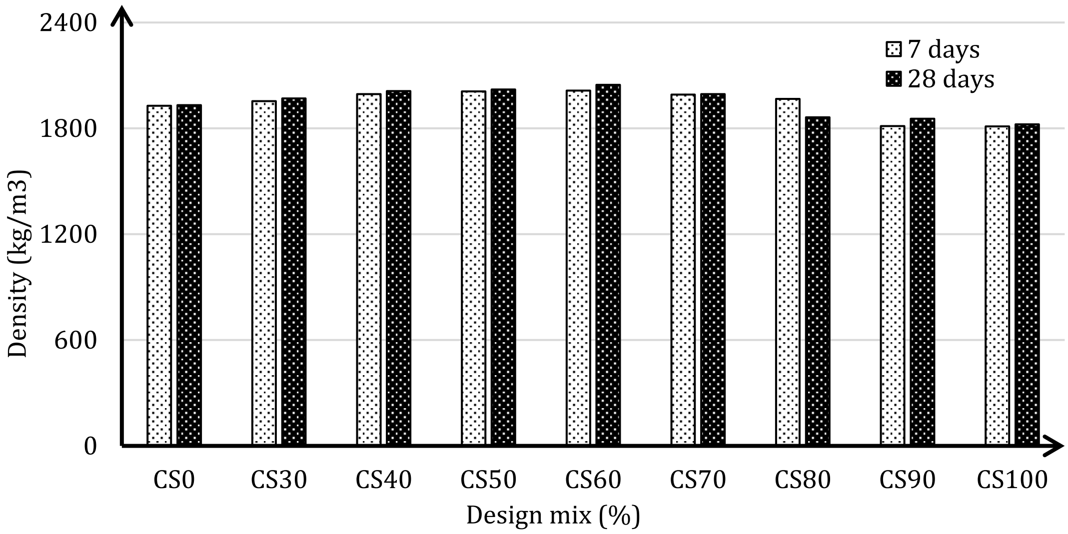


Fig. 6. Density graph of the CS brick at 7 and 28 days of curing (kg/m^3)

3.2.2 Compressive Strength of Bricks

Table 6 presents the compressive strength results for cement-sand bricks incorporating various percentages of cockle shell (CS) as a sand replacement at 7 and 28 days of curing. The trend observed indicates that the compressive strength initially increases with CS replacement up to 60% before declining at higher replacement levels (70%–100%).

Table 6. Compressive strength data for the brick specimen

Design Mix	Compressive strength for 7 days (MPa)	Compressive improvement compared to control mixture* (%)	Compressive strength for 28 days (MPa)	Compressive improvement compared to control mixture* (%)
CS0	6.5	-	7.93	-
CS30	11.2	72.31	11.97	50.95
CS40	12.23	88.15	13.27	67.34
CS50	12.57	93.38	13.63	71.88
CS60	11.8	81.84	13.83	74.40
CS70	11.7	80.00	12.3	55.11
CS80	11.57	78.00	11.96	50.82
CS90	8.63	32.77	11.43	44.14
CS100	6.91	6.31	7.17	-9.58

The increase in strength from CS0% to CS60% can be attributed to the higher specific gravity of cockle shell particles, which may have contributed to enhanced densification and interlocking within the cement matrix. This aligns with the density trend, where the inclusion of cockle shells up to 60% improved the compactness of the mix, resulting in better load-bearing capacity. The highest compressive strength was recorded at CS60% (13.83 MPa at 28 days), suggesting that this replacement level provides an optimal balance between densification and porosity control. However, beyond CS60%, the compressive strength exhibited a decreasing trend. This reduction is likely due to the increase in porosity and void formation, which weakens interparticle bonding and reduces load transfer efficiency within the mix. The excessive incorporation of cockle shell at CS70%–CS100% may have disrupted particle packing efficiency, leading to a more porous structure that negatively impacts strength development. At CS100%, the lowest compressive strength was recorded (7.17 MPa at 28 days), demonstrating that fully replacing sand with cockle shell significantly compromises mechanical performance.

These findings align with the studies of [29,30], which emphasize that materials with higher porosity and lower density contribute to reduced compressive strength due to increased void content. Similarly, [31] reported a comparable trend, where partial replacement of sand with cockle shell powder (CSP) initially enhanced the compactness of the mix but resulted in strength reduction at higher replacement levels due to increased porosity and weaker bonding. The porosity or void ratio was not measured directly, but the porosity or voids can be indicated by the water absorption (see Subsection 3.2.3) and scanning electron microscopy on the brick surfaces (see Subsection 3.3.2). The absorbed water increased after CS60%, indicating increased porosity or voids, and this was further confirmed by SEM analysis. According to standard specifications set by JKR, cement-sand bricks must achieve a minimum compressive strength of 5.2 MPa. Fig. 7 indicates that all tested replacement levels met this requirement, with even the lowest strength recorded at CS100% (6.91 MPa at 7 days) exceeding the standard.

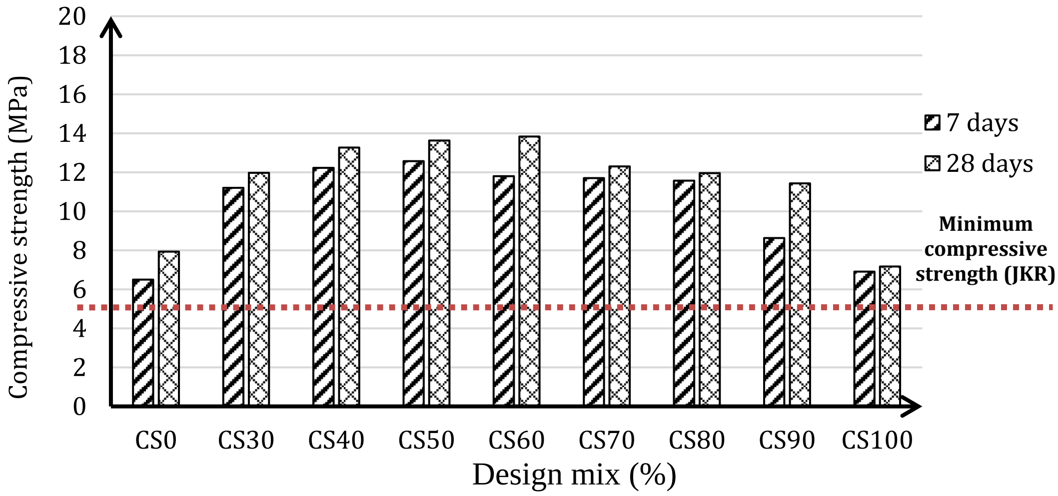


Fig. 7. Compressive strength graph of the CS brick at 7 and 28 days of curing (MPa)

3.2.3 Water Absorption

The water absorption trend of the cement-sand bricks incorporating cockle shell (CS) as a partial sand replacement is illustrated in Fig. 8. The data reveal an initial decline in water absorption from CS0 to CS60, followed by a gradual increase from CS70 onwards. The highest absorption is observed in CS0, while the lowest occurs at CS60. The reduction in water absorption up to CS60 suggests that the inclusion of cockle shell enhances the compactness of the matrix, reducing porosity. However, beyond this threshold, the increasing trend in water absorption for CS70 to CS90 indicates that excessive cockle shell content may disrupt the densification process, leading to higher porosity. Despite the variations, all design mixes remain well below the maximum water absorption limit specified by [27], ensuring compliance with standard requirements. The results highlight the potential of cockle shells as a sustainable material in brick production, balancing porosity and water absorption within acceptable limits.

The results of this study align with previous research findings on water absorption in cement bricks containing cockle shell as a sand replacement. As [32] highlighted, water absorption is the percentage of water retained by a brick when transitioning from a dry to a fully saturated state. A higher porosity within the brick matrix leads to increased water absorption, as stated by [33]. In this study, the trend in water absorption follows a similar pattern, where the incorporation of cockle shell initially reduces water absorption up to CS60% but increases beyond this point, suggesting a shift in porosity levels. Additionally, the relationship between density and water absorption observed in this study agrees with the findings of [34] in their assessment of CSP-modified bricks. As the increase in CSP beyond the optimum replacement level leads to a decline in density and an increase in water absorption due to the formation of additional voids. Similarly, in this study, bricks incorporating CS80% and higher exhibit an increase in water absorption and a decline in both density and compressive strength. The density at CS80% drops to 1863 kg/m^3, marking a 3.57% decrease from CS0%, while the compressive strength declines to 11.96 MPa at 28 days. This inverse relationship between density and water absorption further confirms that excessive cockle shell replacement leads to a more porous structure, diminishing the mechanical properties of the bricks.

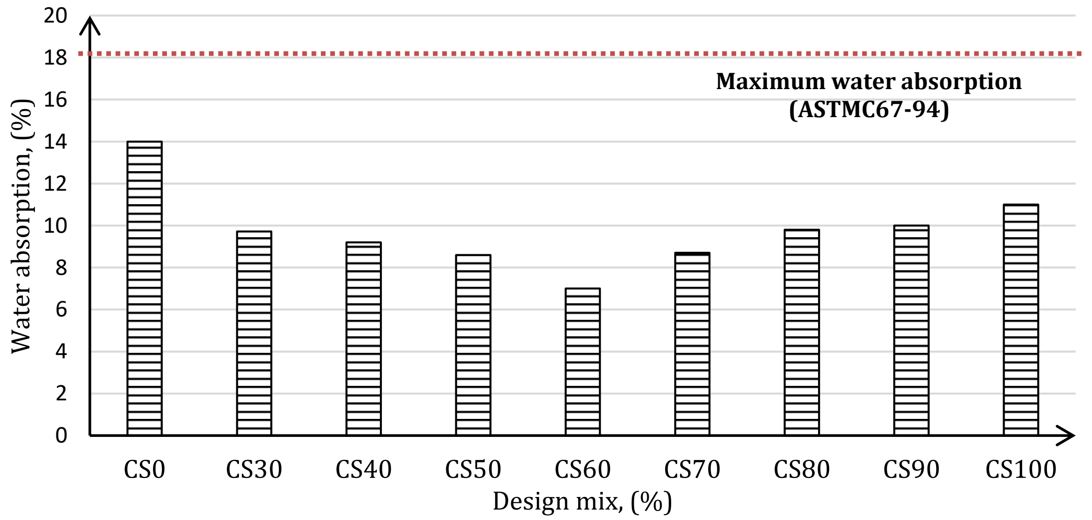


Fig. 8. Water absorption test at 28 days of curing (%)

3.2.4 Initial Rate Absorption (IRA)

The Initial Rate of Absorption (IRA) is a critical factor affecting the water absorption behavior of cement-sand bricks, which influences their durability and bonding efficiency with mortar. As shown in Fig. 9, the IRA values exhibit a decreasing trend from CS0% to CS60%, indicating reduced water absorption due to improved densification and particle interlocking. This aligns with findings by [30], who reported that enhanced material compactness reduces pore connectivity and limits water penetration.

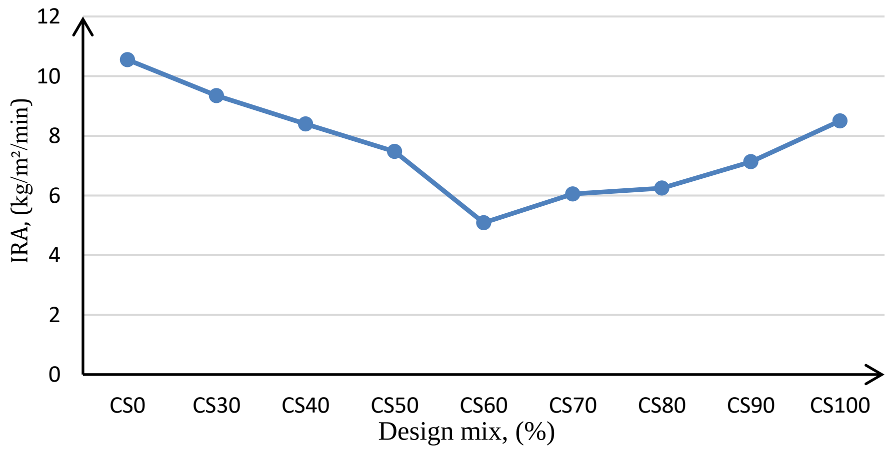


Fig. 9. Initial rate absorption (IRA) test at 28 days of curing (kg/m^2/min)

The lowest IRA value at CS60% suggests optimal porosity reduction, supporting the increase in compressive strength observed at this replacement level. However, beyond CS60%, the IRA values begin to increase, particularly from CS70% to CS100%, indicating a rise in porosity and water absorption. This trend is consistent with the study by [31], which highlighted that excessive incorporation of lightweight materials could disrupt particle packing efficiency, leading to void formation and higher permeability.

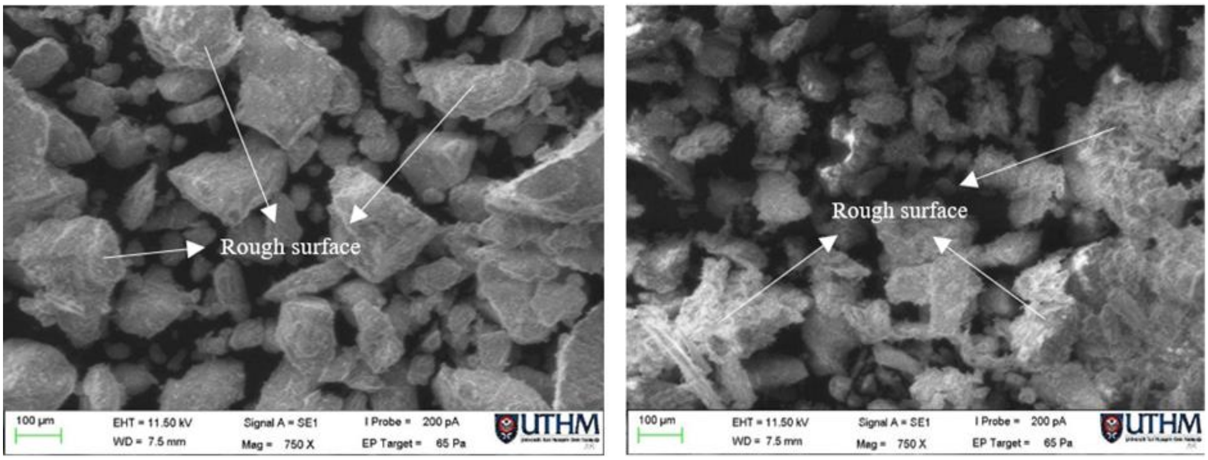
A lower IRA is generally desirable for improved mortar adhesion and long-term durability, as excessive water absorption can weaken the bond between bricks and mortar, potentially leading to structural failure [29]. The increasing IRA beyond CS60% correlates with the reduction in compressive strength, reinforcing the notion that excessive cockle shell content compromises mechanical integrity. These findings suggest that an optimal replacement level of up to 60% cockle shell provides the best balance between reduced water absorption and mechanical performance. Beyond this threshold, the increase in IRA indicates a more porous structure, which may negatively impact the brick's performance in construction applications.

3.3. Scanning Electron Microscope (SEM) Analysis

This sub-section presents the microstructural analysis of sand, cockle shell and brick specimens using Scanning Electron Microscope (SEM).

3.3.1 SEM on Sand and Cockle Shell

Fig. 10 shows the morphologies of (a) sand and (b) cockle shell under 750x magnification. Sand particles appear relatively angular with limited surface roughness and fewer micro-protrusions. In contrast, cockle shell shows a rougher and more irregular surface texture with a higher degree of angularity and porous microstructures. This increased surface roughness enhances mechanical interlocking between the particles and the cement paste. According to [35], the rough surface of cockle shells enhances bonding properties and contributes to improved mechanical performance of cementitious products. Additionally, the irregular shape and porous nature of cockle shells provide more surface area for hydration product nucleation, contributing to improved matrix densification. These characteristics allow cockle shells to fill voids more effectively and create a tighter bond with the cement matrix, ultimately improving the overall microstructure and reducing porosity in cement-sand brick formulations.

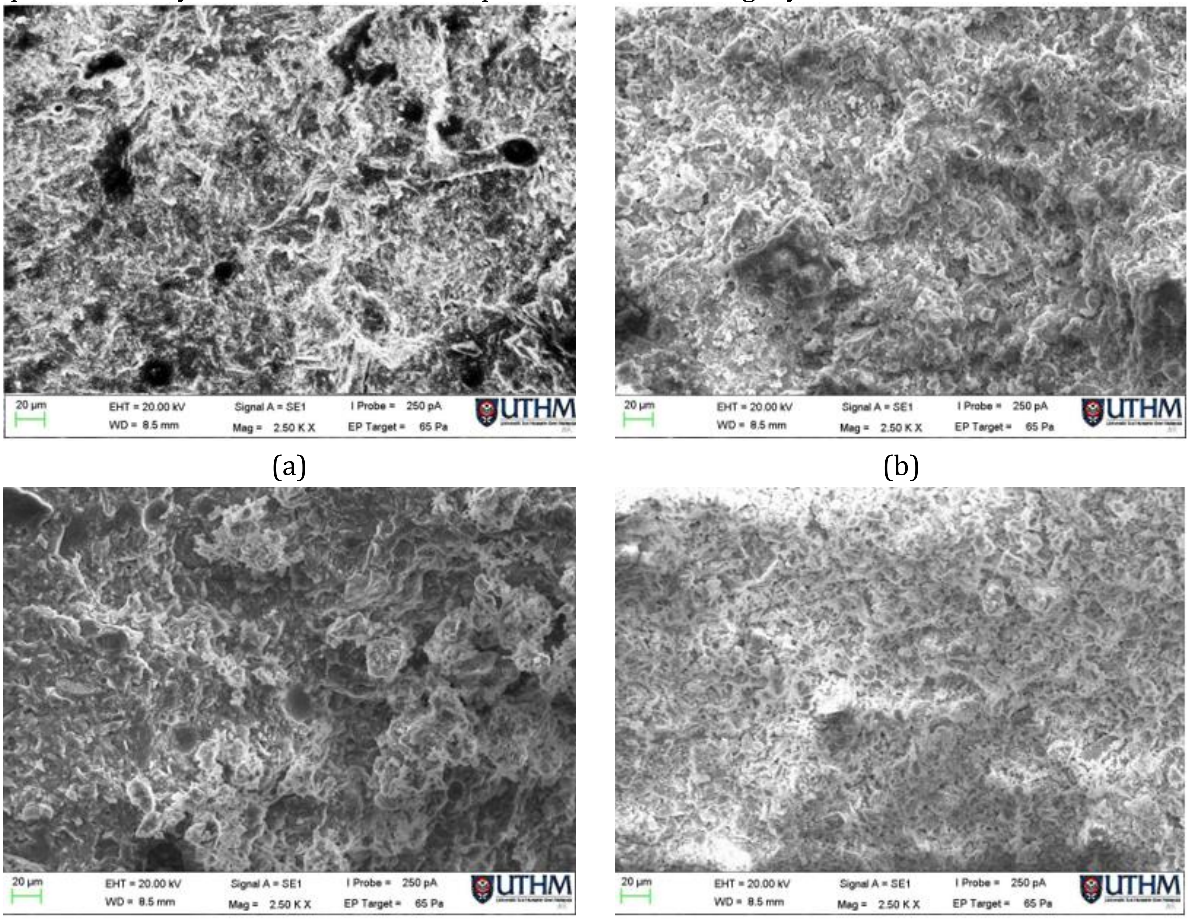


(a) (b)

Fig. 10. Morphologies of (a) sand, (b) cockle shells

3.3.2 SEM on Brick Specimens

The presence of voids and porosity in the brick affects the mechanical properties of the brick. As seen in the SEM image in Fig. 11, the more prominent and larger the voids, the lower the material's density will be. At (a) CS0%, the control sample exhibited a relatively dense and compact matrix with minimal visible pores, indicating effective cement hydration and strong interfacial bonding between the cement paste and natural sand. The (b) CS30%, a slight increase in pore distribution was observed, although the matrix remained well integrated, suggesting the partial inclusion of cockle shell did not significantly disrupt the internal structure. The micrograph at (c) CS60%, displayed a more refined and tightly packed matrix, with reduced pore size and improved particle interlocking, which correlates with the highest compressive strength and lowest water absorption recorded in this study. Conversely, at (d) CS100%, the microstructure became noticeably more porous and less cohesive, with larger and irregular voids, indicating poor bonding and greater microstructural discontinuity. These observations support the mechanical test results and affirm that 60% cockle shell replacement yields the most favourable internal structure, while excessive replacement beyond this threshold compromises matrix integrity.



(a) (b) (c) (d)

Fig. 11. SEM Microstructure of brick at different CS replacement levels (a) CS0% (b) CS30% (c) CS60% and (d) CS100%

4. Conclusion

The improved performance observed at 60% cockle shell replacement in this study, contrasting with the commonly reported optimum of 30% in previous research can be attributed to methodological enhancements in material processing and mix control. Constituent material testing revealed that cockle shells possessed a slightly higher density (1687.27 kg/m^3) and specific gravity (2.73) compared to sand (1642.67 kg/m^3 and 2.66, respectively), which contributed to better compactness and densification of the cement-sand matrix, enhancing particle interlocking and strength development. While previous studies generally identified the optimum replacement level of cockle shell below 30% such as [17,18] identified 30% as the upper limit for cockle shell replacement due to early strength reduction and increased porosity, their methodologies involved coarser shell particles without stringent size control, resulting in non-uniform particle packing and weaker bond formation. In contrast, the present study utilized finely crushed and sieved cockle shell particles (<5 mm), with the majority falling between 2.0–4.75 mm, closely matching natural sand gradation. This size compatibility promoted improved matrix packing, reduced void content, and enhanced interfacial bonding between particles and cement paste. Furthermore, this study consistently applied a 1:6 cement-to-sand ratio and a 0.5 water–cement ratio under controlled ambient curing conditions, eliminating hydration inconsistencies and ensuring strength development was influenced primarily by the replacement material. As a result, compressive strength continued to increase up to 60% replacement, achieving a peak of 13.83 MPa at 28 days, a 74% improvement over the control mix and significantly surpassing the JKR minimum requirement of 5.2 MPa for non-load-bearing bricks.

Water absorption (10.12%) and initial rate of absorption (IRA, 4.32 kg/m^2·min) also followed the same trend as compressive strength, decreasing up to 60% due to improved compactness and pore structure, before increasing at higher replacement levels due to excessive porosity. SEM microstructural analysis further confirmed a denser matrix with fewer voids at 60% replacement, supporting the hypothesis that optimized gradation and curing contributed to matrix densification. Although Khalid et al. [19] achieved higher strength using 55% recycled concrete aggregate (RCA) with a richer 1:3 mix ratio, the cockle shell bricks in this study offer better sustainability and lower cost, making them more suitable for eco-efficient brick production. Therefore, the deviation from the conventional 30% threshold is not due to inconsistency, but rather the outcome of improved processing techniques and mix design, which enabled high-volume cockle shell incorporation without compromising structural performance. Practically, the developed bricks are appropriate for non-structural applications such as internal partition walls, given their mechanical properties exceed the minimum standard required.

From an economic perspective, Malaysia's sand consumption reached approximately 1.49 million metric tons in 2023, projected to rise to 1.65 million tons by 2028 [36]. With river sand costing RM50–80 per ton ex-factory (≈ RM 8–13/m^3) and additional costs from royalties and logistics inflating prices by up to 80%, the adoption of cockle shell as a replacement presents considerable savings. As a zero-cost aquaculture by-product, cockle shell eliminates raw material sourcing and disposal fees. Assuming an annual production of 1 million bricks, 60% replacement could substitute approximately 22,500 tons of sand, saving RM1.1–1.8 million in material costs annually, excluding royalty and transport savings. Operationally, this may reduce brick production costs by 10%–20% per ton, while diverting waste from landfills and supporting circular economy principles. In conclusion, this study demonstrates that high-volume cockle shell incorporation up to 60% not only meets technical standards for non-load-bearing bricks but also contributes to cost-effective, eco-efficient construction. It reduces sand dependency, mitigates waste disposal issues, and promotes sustainable resource use, making it a viable strategy for green building practices in coastal and resource-constrained regions. However, this study is limited to short-term laboratory-scale testing. Long-term durability performance and field-scale validations were not covered and are recommended for future research to fully confirm the practical applicability of cockle shell-based bricks under real environmental conditions, including different climatic zones, and freeze-thaw cycles.

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